EFFECTS OF FLUX APPLICATION AND MELTING PARAMETERS IN INVESTMENT CASTING OF PURE ALUMINIUM BY IN-SITU MELTING TECHNIQUE

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I dedicate this thesis to my lovely, husband, children and family.

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ABSTRACT

Investment cast aluminium suffers porosity defect attributed to the complex combination of various factors including melt quality, casting process parameter and pouring technique. Even though, melt treatment and controlled of the process parameter have promising result, however turbulence developed during pouring of molten aluminium increasing the formation of porosity as a result of the entrainment of the surface oxide (Al_2O_3) film known as bifilm. Currently, turbulence free filling system was applied in casting process using tilt casting, bottom filling integrated with low pressure and also in-situ casting or in-situ melting techniques to address the porosity problem. However, in-situ melting technique has not been studied to reduce the porosity of the investment cast aluminium due to the oxidation of the granular aluminium occurs during heating hinders the complete melting of the granules. This research develops a procedure for investment casting of aluminium granules of 99.4% purity by in-situ melting technique. The aluminium granules were filled in ceramic moulds and heated at four different temperatures of 700, 750, 800 and 850^oC for 30 and 60 min in a high temperature muffle furnace in ambient. As the heating temperature and duration were increased, the aluminium granules incompletely melt and produced a casting, however the granules agglomerate and replicate the shape of the ceramic mould. The aluminium granules oxidised during heating, encapsulated by a layer of complex oxides composed of stable [α-Al_2O_3], metastable [γ-Al_2O_3] and hydroxides. The thickness of the oxide layer formed on the surface of the air-heated granules increased as the heating temperature and duration were increased. The aluminium granules then were heated at the temperature of 850^oC for 30 min in argon environment at the flow rate of argon gas 0.5, 2.5 and 5 ℓ/min to reduce the oxidation of the aluminium granules. The thickness of the oxide layer formed on the argon-heated granule (5 ℓ/min) was reduced by 60%, but failed to produce a casting. NaCl-KCl flux was applied, which was mixed and sprinkled on the aluminium granules at the Al:Flux ratio of 1:0.2, 1:0.25 and 1:0.33 and heated at the temperature of 850^oC for 30 min to break the oxide layer that encapsulate the granules during heating. At the Al:Flux ratio of 1:0.33, 99% of the aluminium granules were successfully melted and produced a casting. The granules began melting at the temperature range 657.2 to 658.4^oC and completely melted in 16 min with final melting temperature between 660.1 and 660.6^oC. The average porosity level of the casting was 1.22%, which is lower than the investment cast aluminium produced by current pouring technique (2.48%). The low porosity level was attributed to micro-intergranular porosity present in the casting due to volume shrinkage. Investment casting of aluminium granules by in-situ melting technique with application of NaCl-KCl flux at the Al:Flux ratio of 1:0.33 mixed and sprinkled on the granules heated at the temperature of 850^oC for 30 min producing low porosity aluminium casting.

ABSTRAK

Tuangan pelaburan aluminium mengalami kecacatan keliangan dikaitkan dengan kombinasi kompleks beberapa faktor termasuk kualiti leburan, parameter proses tuangan dan teknik menuang. Walaupun rawatan leburan dan kawalan parameter proses mempunyai hasil yang menjanjikan, tetapi gelora terjadi semasa menuang leburan aluminium yang mana meningkatkan pembentukan keliangan akibat kehadiran filem permukaan oksida (Al_2O_3) yang dinamakan sebagai *bifilm*. Kini, sistem isian bebas gelora telah diaplikasi dalam proses tuangan dengan menggunakan tuangan condong, isian dari bawah dengan tekanan rendah, dan juga tuang secara di situ atau lebur secara di situ untuk mengatasi masalah keliangan. Walaubagaimanapun, teknik lebur secara di situ masih belum dikaji untuk mengurangkan keliangan tuangan pelaburan aluminium kerana pengoksidaan butiran aluminium berlaku semasa pemanasan yang menghalang butiran aluminium melebur dengan sempurna. Kajian ini menghasilkan prosedur tuangan pelaburan butiran aluminium 99.4% tulen dengan teknik lebur di situ. Butiran aluminium dimasukkan ke dalam acuan seramik dan dipanaskan pada empat suhu berbeza iaitu 700, 750, 800 dan 850^{o}C selama 30 dan 60 min di dalam relau *muffle* suhu tinggi secara ambien. Apabila suhu dan tempoh pemanasan dinaikkan, butiran aluminium tidak lebur secara sempurna dan tidak menghasilkan tuangan. Butiran tersebut bergumpal mengikut bentuk acuan seramik. Butiran aluminium teroksida, dirangkum oleh lapisan oksida kompleks [α-Al_2O_3] stabil, [γ-Al_2O_3] metastabil dan hidroksida. Ketebalan lapisan oksida di permukaan butiran yang dipanaskan dalam udara meningkat apabila suhu dan tempoh pemanasan dinaikkan. Seterusnya, butiran aluminium dipanaskan pada suhu 850^{o}C selama 30 min dalam persekitaran argon dengan kadar alir gas argon 0.5, 2.5 and 5 ℓ/min untuk mengurangkan pengoksidaan butiran aluminium. Ketebalan lapisan oksida di permukaan butir aluminium yang dipanaskan dalam argon (5 ℓ/min) berkurang sebanyak 60%, tetapi gagal menghasilkan tuangan. Fluks NaCl-KCl digunakan, dicampur dan ditabur ke atas butiran aluminium pada nisbah Al:Fluks 1:0.2, 1:0.25 and 1:0.33 dan dipanaskan pada suhu 850^{o}C selama 30 min untuk memecahkan lapisan oksida yang merangkum butiran. Pada nisbah Al:Fluks 1:0.33, 99% butiran aluminium berjaya dilebur dan menghasilkan tuangan. Butiran aluminium mula mencair pada julat suhu 657.2 ke 658.4^{o}C dan lengkap melebur dalam masa 16 min dengan julat suhu lebur akhir 660.1 ke 660.6^{o}C. Purata tahap keliangan tuangan ialah 1.22% iaitu lebih rendah berbanding tuangan pelaburan aluminium yang dihasilkan dengan teknik tuangan semasa (2.48%). Tahap keliangan yang rendah dikaitkan dengan keliangan mikro-antarabutiran yang hadir dalam tuangan akibat pengecutan isipadu. Tuangan pelaburan butiran aluminium dengan teknik lebur di situ serta aplikasi fluks NaCl-KCl dengan nisbah Al:Fluks 1:0.33 dicampur dan ditabur atas butiran aluminium serta dipanaskan pada suhu 850^{o}C selama 30 min menghasilkan tuangan aluminium dengan tahap keliangan yang rendah.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

REFERENCES

Adrian, C., Andreas, G., Carol, P., & Vasile, L. D. (2013). Industrial Parts for Investment Casting Built on the Rapid Prototyping Systems. Applied Mechanics and Materials, 371, 250–254.

ANSI H35.1-1988 (1988). Alloy and Temper Designation Systems for Aluminum. United States: American National Standards Institute (ANSI).

Anžel, I. (2000). High Temperature Oxidation of Metals and Alloys. Metalurgija-Journal of Metallurgy, 325–336.

Apelian, D. (2009). Enabling Tools for Improved Performance Aluminum Cast Alloys. Wheeling, IL: North American Die Casting Association

ASM Handbook Volume 2: Properties and Selection: Nonferrous Alloys and Special-Purpose Materials. (1990). ASM International

Bala, K. C., Khan, R. H., Abolarin, M. S., & Abubakre, O. K. (2013). Investigation on the Rate of Solidification and Mould Heating in the Casting of Commercially Pure Aluminium in Permanent Moulds of varying Thicknesses, 6(1), 33–37.

Barbosa, J., & Puga, H. (2017). Ultrasonic melt processing in the low pressure investment casting of Al alloys. Journal of Materials Processing Technology, 244, 150–156.doi:org/10.1016/j.jmatprotec.2017.01.031

Beeley, P. (2001). Foundry Technology (2nd ed.). Oxford: Butterworth-Heinemann.

Bemblage, O., & Karunakar, D. B. (2011). A Study on the Blended Wax Patterns in Investment Casting Process. In Proceedings of the World Congress on Engineering 2011 (Vol. I).

Brum, F. J. B., Amico, S. C., Vedana, I., & Spim, J. A. (2009). Microwave dewaxing applied to the investment casting process. Journal of Materials Processing Technology, 209(7), 3166–3171. doi:org/10.1016/j.jmatprotec.2008.07.024

Budgen, N. F. (1947). Aluminium and Its Alloy (2nd ed). London: Sir Isaac Pitman & Sons Ltd.

Callister, W. D. J. (2003). Materials Science and Engineering An Introduction (6th ed.). New York: John Wiley & Sons Inc.

Campbell, J. (1991). Castings. Burlington: Butterworth-Heinemann.

Campbell, J. (2006). An Overview of the Effects of Bifilms on the Structure and Properties of Cast Alloys. Metallurgical and Materials Transactions B, 37(December), 857–863.

Campbell, J. (2011). Complete Casting Handbook Metal Casting Processes, Metallurgy, Techniques and Design (1st ed.). Oxford: Butterworth-Heinemann.

Cardarelli, F. (2008). Ceramics, Refractories , and Glasses. In Materials Handbook: A Concise Desktop Reference (2nd ed., pp. 593–689). London: Springer-Verlag London. doi:org/10.1007/978-1-84628-669-8

Chen, Y., Jong, S., & Hwang, W. (1996). Effects of cooling rate on latent heat released mode of near pure aluminium and aluminium – silicon alloys. Materials Science and Technology, 12(7), 539–544.

Chen, Y., Xiao, S., Tian, J., Xu, L., & Chen, Y. (2011). Effect of particle size distribution on properties of zirconia ceramic mould for TiAl investment casting. Transactions of Nonferrous Metals Society of China, 21(May), s342–s347. doi:org/10.1016/S1003-6326(11)61603-8

Coker, E. N. (2013). The oxidation of aluminum at high temperature studied by Thermogravimetric Analysis and Differential Scanning Calorimetry. Springfield.

Craig, B. D. (1991). Fundamental Aspects of Corrosion Films in Corrosion Science. New York, NY: Plenum Press, New York.

Davies, D. P., & Jenkins, S. L. (2016). Assessment of a controlled solidification aluminium investment casting technique for use in helicopter gearboxes. Materials Science and Engineering: A, 651, 449–460. doi:org/10.1016/j.msea.2015.10.028

Dispinar, D., & Campbell, J. (2007). Effect of casting conditions on aluminium metal quality. Journal of Materials Processing Technology, 182(1–3), 405–410.doi:org/10.1016/j.jmatprotec.2006.08.021

Dispinar, D., & Campbell, J. (2011). Porosity, hydrogen and bifilm content in Al alloy castings. Materials Science and Engineering: A, 528(10–11), 3860–3865.doi:org/10.1016/j.msea.2011.01.084

Dispinar, D., & Campbell, J. (2011). Porosity, hydrogen and bifilm content in Al alloy castings. Materials Science and Engineering: A, 528(10–11), 3860–3865.doi:org/10.1016/j.msea.2011.01.084

Dispinar, D., Akhtar, S., Nordmark, a., Di Sabatino, M., & Arnberg, L. (2010). Degassing, hydrogen and porosity phenomena in A356. Materials Science and Engineering: A, 527(16–17), 3719–3725.doi:org/10.1016/j.msea.2010.01.088

Dos Santos, S. L., Antunes, R. A., & Santos, S. F. (2015). Influence of injection temperature and pressure on the microstructure, mechanical and corrosion properties of a AlSiCu alloy processed by HPDC. Materials and Design, 88, 1071–1081.doi:org/10.1016/j.matdes.2015.09.095

Drápala, J., & Kruchař, L., (2015). Metallurgy of Pure Metals. Study Report. Czech Republic: Technical University of Ostrava

EAA Aluminium penetration in cars Final Report. (2012). Brussels. Retrieved from http://www.alueurope.eu. Accessed on 20th May 2018.

Elsebaie, O., Mohamed, A. M. A., Samuel, A. M., Samuel, F. H., & Al-Ahmari, A. M. A. (2011). The role of alloying additives and aging treatment on the impact behavior of 319 cast alloy. Materials & Design, 32(6), 3205–3220. doi:org/10.1016/j.matdes.2011.02.047

Erbas, K. C. (2013). Suggestion of a New Model for Newtonian Thermal Analysis of Solidification. Middle East Technical University:PhD Thesis.

Farahany, S., Ourdjini, A., Idris, M. H., & Shabestari, S. G. (2013). Computer-aided cooling curve thermal analysis of near eutectic Al–Si–Cu–Fe alloy. Journal of Thermal Analysis and Calorimetry, 114(2), 705–717. doi:org/10.1007/s10973-013-3005-7

Galetz, M. C., Montero, X., Mollard, M., Günthner, M., Pedraza, F., & Schütze, M. (2014). The role of combustion synthesis in the formation of slurry aluminization. Intermetallics, 44, 8–17. doi:org/10.1016/j.intermet.2013.08.002

Gaustad, G., Olivetti, E., & Kirchain, R. (2012). Improving aluminum recycling: A survey of sorting and impurity removal technologies. Resources, Conservation and Recycling, 58, 79–87.doi:org/10.1016/j.resconrec.2011.10.010

Goodisman, J. (1980). Surface Tensions of Molten Salt Mixtures. Journal of Colloid and Interface Science, 73(1), 115–123.

Goswami, R. (1997). Melting and Superheating Metals and Alloys, 42(97), 287–300.

Grieveson, P., E. C. Partington, & Terry, B. (1998). Self-sustaining oxidation of liquid aluminium and its alloys containing magnesium and silicon. Journal of Materials Science, 33, 2447–2455.

Gunasegaram, D. R., Givord, M., O'Donnell, R. G., & Finnin, B. R. (2013). Improvements engineered in UTS and elongation of aluminum alloy high pressure die castings through the alteration of runner geometry and plunger velocity. Materials Science and Engineering A, 559, 276–286. doi:org/10.1016/j.msea.2012.08.098

Haghayeghi, R., Bahai, H., & Kapranos, P. (2012). Effect of ultrasonic argon degassing on dissolved hydrogen in aluminium alloy. Materials Letters, 82, 230–232. doi:org/10.1016/j.matlet.2012.05.112

Harding, R. A., Wickins, M., Wang, H., Djambazov, G., & Pericleous, K. A. (2011). Development of a turbulence-free casting technique for titanium aluminides. Intermetallics, 19(6), 805-813. doi:org/10.1016/j.intermet.2010.11.022

Hasani, S., Panjepour, M., & Shamanian, M. (2012b). The oxidation mechanism of pure aluminum powder particles. Oxidation of Metals, 78(3-4), 179-195. doi:org/10.1007/s11085-012-9299-1

Hasani, S., Panjepour, M., & Shamanian, M. (2012a). Oxidation and Kinetic Analysis of Pure Aluminum Powder under Non-isothermal Condition 1:385. Open Access Scientific Report.

Hirsch, J. (2011). Aluminium in Innovative Light-Weight Car Design . Materials Transactions, 52(5), 818–824.doi:org/10.2320/matertrans.L-MZ201132

Horáček, M., Charvát, O., Pavelka, T., Sedlák, J., Madaj, M., Nejedlý, J., & Dvořáček, J. (2011). Medical implants by using RP and investment casting technologies, *Proceeding of 69th World Foundry Congress* (February 2010). Hangzhou, China: WFC, 107–111.

Ingels, L. (2001). Purging principles and practice (3rd ed.) Washington: American Gas Association. doi:org/10.1520/G0154-12A

Jafari, H., Idris, M. H., & Ourdjini, A. (2011). High temperature oxidation of AZ91D magnesium alloy granule during in-situ melting. Corrosion Science, 53(2), 655–663. doi:org/10.1016/j.corsci.2010.10.012

Jafari, H., Idris, M. H., & Ourdjini, A. (2013). A Review of Ceramic Shell Investment Casting of Magnesium Alloys and Mold-Metal Reaction Suppression

A Review of Ceramic Shell Investment Casting of Magnesium Alloys and Mold-Metal Reaction Suppression. Materials and Manufacturing Processes, 28, 843-856. doi:org/10.1080/10426914.2013.811729

Jafari, H., Idris, M. H., Ourdjini, A., & Farahany, S. (2013). In situ melting and solidification assessment of AZ91D granules by computer-aided thermal analysis during investment casting process. Materials & Design, 50, 181–190. doi:org/10.1016/j.matdes.2013.02.035

Jafari, H., Idris, M. H., Ourdjini, A., & Kadir, M. R. A. (2013). Influence of Flux on Melting Characteristics and Surface Quality of In-Situ Melting AZ91D. Materials and Manufacturing Processes, 28(2), 148–153. doi.org/10.1080/10426914.2012.746787

Jafari, H., Idris, M. H., Ourdjini, A., Farahany, S., & Kadir, M. R. A. (2012). Characterization of AZ91D Granules Covered with a Flux during In-Situ Melting. Particle & Particle Systems Characterization, 29(4), 263–272. doi:org/10.1002/ppsc.201100044

American Foundry Society. (1992). Solid fluxing practices for aluminum melting in Modern Casting. Jeanneret, J. L.

Jeurgens, L. P. H., Sloof, W. G., Tichelaar, F. D., & Mittemeijer, E. J. (2000). Thermodynamic stability of amorphous oxide films on metals: Application to aluminum oxide films on aluminum substrates. Physical Review B, 62(7), 4707–4719. doi:org/10.1103/PhysRevB.62.4707

Jeurgens, L. P. H., Sloof, W. G., Tichelaar, F. D., & Mittermeijer, E. J. (2002). Growth kinetics and mechanics of aluminum-oxide films formed by thermal oxidation of aluminum. Thin Solid Films, 92, 1649–1656.

Jiang, W. ming, Fan, Z. tian, Liu, D. jun, Dong, X., Wu, H., & Wang, H. S. (2012). Effects of Process Parameters on Internal Quality of Castings during Novel Casting. Materials and Manufacturing Processes, 28(1), 48–55. doi:org/10.1080/10426914.2012.681414

Jiang, W., Fan, Z., Liu, D., Liao, D., Dong, X., & Zong, X. (2013). A Correlation of microstructure with mechanical properties and fracture behavior of A356-T6 aluminum alloy fabricated by expendable pattern shell casting with vacuum and low-pressure , gravity casting and lost foam casting. Materials Science and Engineering A, 560, 396–403.

Jin, C. K., & Kang, C. G. (2011). Fabrication process analysis and experimental verification for aluminum bipolar plates in fuel cells by vacuum die-casting. Journal of Power Sources, 196(20), 8241–8249. doi:org/10.1016/j.jpowsour.2011.05.073

Jolly, M. (2005). Prof. John Campbell's ten rules for making reliable castings. The Minerals, Metals & Materials Society, 57(5), 19–28. doi:org/10.1007/s11837-005-0091-4

Jones, S., & Yuan, C. (2003). Advances in shell moulding for investment casting. Journal of Materials Processing Technology, 135(2–3), 258–265. doi:org/10.1016/S0924-0136(02)00907-X

Kalpakjian, S., & Schmid, S. R. (2010). Manufacturing Engineering and Technology (6th ed.). Jurong, Singapore: Prentice Hall.

Kim, I. S., & Lee, S. J. (1998). Study of the role of Mg and Zn in the directive oxidation of Al alloys. Journal of Materials Science Letters, 17, 1357–1362.

Kim, K. (2014). Formation of Fine Clusters in High-Temperature Oxidation of Molten Aluminum. Metallurgical and Materials Transactions A, 45(8), 3650–3660. doi:org/10.1007/s11661-014-2270-9

Kirshenbaum, A. D., Cahill, J. A., & Mcgonigal, P. J. (1962). The Density of Liquid NaCl and KCl and An Estimate of Their Critical Constants Together with Those of Their Alkali Halides. Journal of Inorganic and Nuclear Chemistry, 24,1287-1296.

Kolarik, V., Juez-lorenzo, M. M., & Fietzek, H. (2011). Oxidation of Micro-Sized Spherical Aluminium Particles. Materials Science Forum, 696, 290–295.

Kondic, V. (1968). Metallurgical Principles of Founding. London: Edward Arnold.

Kumar, P., Ahuja, I. S., & Singh, R. (2016). Experimental investigations on hardness of the biomedical implants prepared by hybrid investment casting. Journal of Manufacturing Processes, 21, 160–171. doi:org/10.1016/j.jmapro.2016.01.001

Levin, I., & Brandon, D. (1998). Metastable Alumina Polymorphs: Crystal Structures and Transition Sequences. Journal of the American Ceramic Society, 81(8), 1995–2012.doi:org/10.1111/j.1151-2916.1998.tb02581.x

Li, C., Yang, H., Ren, Z., Ren, W. L., & Wu, Y. Q. (2010). On Nucleation Temperature of Pure Aluminum in Magnetic Fields. Progress In Electromagnetics Research, 15, 45–52.

Li, D. Z., Campbell, J., & Li, Y. Y. (2004). Filling system for investment cast Ni-base turbine blades. Journal of Materials Processing Technology, 148(3), 310–316. doi:org/10.1016/j.jmatprotec.2004.02.032

Li, Y. M., & Li, R. D. (2001). Effect of the casting process variables on microporosity and mechanical properties in an investment cast aluminium alloy. Science and Technology of Advanced Materials, 2, 277–280.

Liu, S. G., Cao, F. Y., Zhao, X. Y., Jia, Y. D., Ning, Z. L., & Sun, J. F. (2015). Characteristics of mold filling and entrainment of oxide film in low pressure casting of A356 alloy. Materials Science and Engineering A, 626, 159–164. doi:org/10.1016/j.msea.2014.12.058

Lun Sin, S., Dubé, D., & Tremblay, R. (2008). An investigation on microstructural and mechanical properties of solid mould investment casting of AZ91D magnesium alloy. Materials Characterization, 59(2), 178–187. doi:org/10.1016/j.matchar.2007.04.026

Lyon, R. N., (1954). Liquid-Metals Handbook. AGuid to the Use of Liquid Metals as Heat-Transfer Media. Oak Ridge National Laboratory.

Majidi, O., Shabestari, S. G., & Aboutalebi, M. R. (2007). Study of fluxing temperature in molten aluminum refining process. Journal of Materials Processing Technology, 182(1-3), 450-455. doi:org/10.1016/j.jmatprotec.2006.09.003

Martienssen, W., & Warlimont, H. (Eds.). (2005). Metals. In Springer Handbook of Condensed Matter and Materials Data (161–422). Springer Berlin Heidelberg, New York.

Miller, W. S., Zhuang, L., Bottema, J., Wittebrood, A. J., & Smet, P. De. (2000). Recent development in aluminium alloys for the automotive industry, 280, 37–49.

Miresmaeili, S. M. (2009). Effect of Strontium on the Oxidation Behavior of Liquid Al–7Si Alloys. Oxidation of Metals, 71(1–2), 107–123. doi:org/10.1007/s11085-009-9136-3

Mishra, R. R., & Sharma, A. K. (2017). Structure-property correlation in Al–Zn –Mg alloy cast developed through in-situ microwave casting. Materials Science & Engineering A, 688, 532–544. doi:org/10.1016/j.msea.2017.02.021

Mishra, S., & Ranjana, R. (2010). Reverse Solidification Path Methodology for Dewaxing Ceramic Shells in Investment Casting Process. Materials and Manufacturing Processes, 25(12), 1385–1388. doi:org/10.1080/10426914.2010.496125

Mondolfo, L. F. (1976). Aluminum Alloys: Structure and Properties. London, Boston: Butterworth & Co.

Niklas, A., Abaunza, U., Fernández-Calvo, A. I., Lacaze, J., & Suárez, R. (2011). Thermal analysis as a microstructure prediction tool for A356 aluminium parts solidified under various cooling conditions. China Foundry, 8(1), 89–95.

Noirfontaine, M. N., Baldinozzi, G., Barthés-Labrousse, M. G., Kusinski, J., Boëmare, G., Herinx, M., & Feuerbacher, M. (2010). High Temperature Oxidation of the Al_3Mg_2 Complex Metallic Alloy. Oxidation of Metals, 73, 219–232. doi:org/10.1007/s11085-009-9176-8

Omar, M. F. M., Sharif, S., Ibrahim, M., Hehsan, H., Busari, M. N. M., & Hafsa, M. N. (2012). Evaluation of Direct Rapid Prototyping Pattern for Investment Casting. Advanced Materials Research, 463–464, 226–233. doi:org/10.4028/www.scientific.net/AMR.463-464.226

Ozdemir, O., Gruzleski, J. E., & Drew, R. a. L. (2009). Effect of Low-Levels of Strontium on the Oxidation Behavior of Selected Molten Aluminum–Magnesium Alloys. Oxidation of Metals, 72(5–6), 241–257. doi:org/10.1007/s11085-009-9158-x

Pattnaik, S., Karunakar, D. B., & Jha, P. K. (2012). Developments in investment casting process-A review. Journal of Materials Processing Technology, 212(11), 2332-2348. doi:org/10.1016/j.jmatprotec.2012.06.003.

Petrovic, J., & Thomas, G. (2008). Reaction of aluminum with water to produce hydrogen. Retrieved from http://scholar.google.com/scholar. Accessed on 20 May 2018.

Pierre Papon, Jacques Leblond, P. H. E. M. (2002). 3 Phase Transitions in Liquids and Solids : Solidification and Melting. The Physics of Phase Transitions (2nd ed.) 79–124. Berlin, Heidelberg: Springer-Berlin.

Polmear, I. (2006). Light Alloys From Traditional Alloys to Nanocrystals (4th ed.). Oxford: Butterworth-Heinemann.

Prescott, R., & Graham, M. J. (1992). The Formation of Aluminium Oxide Scales on High-Temperature Alloys. Oxidation of Metals, 38(3/4), 233–254.

Previtali, B., Pocci, D., & Taccardo, C. (2008). Application of traditional investment casting process to aluminium matrix composites. Composites Part A: Applied Science and Manufacturing, 39(10), 1606–1617. doi:org/10.1016/j.compositesa.2008.07.001

Puga, H., Barbosa, J., Azevedo, T., Ribeiro, S., & Alves, J. L. (2016). Low pressure sand casting of ultrasonically degassed Al7SiMg alloy: Modelling and experimental validation of mould filling. Materials & Design, 94, 384–391. doi:org/10.1016/j.matdes.2016.01.059

Puga, H., Barbosa, J., Seabra, E., Ribeiro, S., & Prokic, M. (2009). The influence of processing parameters on the ultrasonic degassing of molten AlSi9Cu3 aluminium alloy. Materials Letters, 63(9–10), 806–808. doi:org/10.1016/j.matlet.2009.01.009

Puga, H., Barbosa, J., Soares, D., Silva, F., & Ribeiro, S. (2009). Recycling of aluminium swarf by direct incorporation in aluminium melts. Journal of Materials Processing Technology, 209(11), 5195–5203. doi:org/10.1016/j.jmatprotec.2009.03.007

Puri, P., & Yang, V. (2010). Thermo-mechanical behavior of nano aluminum particles with oxide layers during melting. Journal of Nanoparticle Research, 12(8), 2989–3002. doi:org/10.1007/s11051-010-9889-2

Rani, D., & Karunakar, D. B. (2013). Recycling of Pattern Wax In The Investment Casting Process Using Microwave Dewaxing. IOSR Journal of Engineering, 3(5), 5–10.

Rao, P. N. (2001). Manufacturing Technology Foundry, Forming and Welding (2nd ed.). Singapore: Mc Graw Hill.

Rault, L., Allibert, M., & Dubus, A. (1996). In Situ Study of Liquid Al-Mg Alloys Oxidation. Materials Science Forum, 217–222, 165–170.

Russel, A. M., & Kok, L. L. (2005). Structure-Property Relations in Nonferrous Metals. New Jersey: John Wiley & Sons Inc. doi:org/10.1017/CBO9781107415324.004

Sata, T. (1994). Coloration of molten aluminium surface in various atmospheres. Journal of Materials Science, 29, 129–135.

Scamans, G. M., & Birbilis, N. (2010). Corrosion of Aluminum and its Alloys. Shreir's Corrosions (4th ed.). London: Elsevier B.V.

Shih, T.-S., & Liu, Z.-B. (2006). Thermally-Formed Oxide on Aluminum and Magnesium. Materials Transactions, 47(5), 1347–1353. doi:org/10.2320/matertrans.47.1347

Shih, T., & Weng, K. (2004). Effect of A Degassing Treatment on the Quality of Al-7Si and A356 Melts-Degassing Diffusers, 45(6), 1852–1858.

Singh, B., & Kumar, P. (2010). Effect of Process Parameters on Surface Hardness of Ceramic Shell Investmnet Castings. *Proceeding of National Conference on Advancements and Futuristic Trends in Mechanical and Materials Engineering* February 19-20. Punjab, India. (1–5).

Singh, R., & Singh, G. (2014). Cast Component Hardness Comparison for Investment Casting Prepared with Wax and ABS Patterns. Transactions of the Indian Institute of Metals, 68(1), 17–21. doi:org/10.1007/s12666-014-0432-5

Smart, R. F. (1989). High Strength and Integrity Investment Castings. Materials & Design, 10(6), 301–305.

Standard Practice for Numbering Metals and Alloys in the Unified Numbering System (UNS) 1. (2007). http://doi.org/10.1520/E0527-12.Materials. ASTM International. doi:org/ 10.1520/E0527-12.

Standard Specification for Aluminum-Alloy Investment Castings 1. (2012). ASTM International. doi:org/10.1520/B0618

Taylor, J. A. (2012). Iron-containing intermetallic phases in Al-Si based casting alloys. Procedia Materials Science, 1, 19–33. doi:org/10.1016/j.mspro.2012.06.004

Tenorio, J. A. S., & Espinosa, D. C. R. (2002). Effect of salt/oxide interaction on the process of aluminum recycling. Journal of Light Metals, 2(2), 89–93. doi:org/10.1016/S1471-5317(02)00027-5

Tenorio, J. A. S., & Espinosa, De. C. R. (2000). High-Temperature Oxidation of Al – Mg Alloys. Oxidation of Metals, 53, 361–373.

Tenorio, J. A. S., Carboni, M. C., & Espinosa, D. C. R. (2001). Recycling of aluminum-effect of fluoride additions on the salt viscosity and on the alumina dissolution. Journal of Light Metals, 1, 195–198.

Totten E., G., & MacKenzie D., S. (2003). Handbook of Aluminum Volume 2 Alloy Prodcution and Materials Manufacturing (Vol. 2). New York, NY: Marcel Dekker Inc.

Trunov, M. A., Schoenitz, M., Zhu, X., & Dreizin, E. L. (2005). Effect of polymorphic phase transformations in Al_2O_3 film on oxidation kinetics of aluminum powders. Combustion and Flame, 140(4), 310–318. doi:org/10.1016/j.combustflame.2004.10.010

Tsakiridis, P. E. (2012). Aluminium salt slag characterization and utilization-A review. Journal of Hazardous Materials, 217–218, 1–10. doi:org/10.1016/j.jhazmat.2012.03.052

Tsakiridis, P. E., & Oustadakis, P. (2013). Aluminium recovery during black dross hydrothermal treatment. Journal of Environmental Chemical Engineering, 1(1–2), 23–32. doi:org/10.1016/j.jece.2013.03.004

Utigard, T. A., Friesen, K., Roy, R. R., Lim, J., Silny, A., & Dupuis, C. (1998, November). The Properties and Uses of Fluxes in Molten Aluminum Processing. The Minerals, Metals & Materials Society, 38–43.

Vaezi, M., Safaeian, D., & Chua, C. K. (2011). Gas turbine blade manufacturing by use of epoxy resin tooling and silicone rubber molding techniques. Rapid Prototyping Journal, 17(2), 107–115. doi:org/10.1108/13552541111113853

Velasco, F., Guzmán, S., Moral, C., & Bautista, A. (2013). Oxidation of micro-sized aluminium particles: Hollow alumina spheres. Oxidation of Metals, 80(3–4), 403–422. doi:org/10.1007/s11085-013-9408-9

Wang, E. R., Hui, X. D., Wang, S. S., Zhao, Y. F., & Chen, G. L. (2010). Improved mechanical properties in cast Al–Si alloys by combined alloying of Fe and Cu. Materials Science and Engineering: A, 527(29–30), 7878–7884. doi:org/10.1016/j.msea.2010.08.058

Wang, F., Li, F., He, B., & Sun, B. (2013). Microstructure and strength of needle coke modified ceramic casting molds. Ceramics International. doi:org/10.1016/j.ceramint.2013.06.027

Wang, Q. G., & Cáceres, C. H. (1997). Mg Effects on the Eutectic Structure and Tensile Properties of Al-Si-Mg Alloys. Materials Science Forum, 242, 159–164. doi:org/10.4028/www.scientific.net/MSF.242.159

Wang, S., Miranda, a. G., & Shih, C. (2010). A Study of Investment Casting with Plastic Patterns. Materials and Manufacturing Processes, 25(12), 1482–1488. doi:org/10.1080/10426914.2010.529585

Wang, T., Yao, S., & Shen, W. (2015). A submerged-gate casting method. Journal of Materials Processing Technology, 222, 21–26. doi:org/10.1016/j.jmatprotec.2015.02.034

Wang, Y., & Xiong, Y. (2000). Effects of beryllium in Al – Si – Mg – Ti cast alloy, Materials Science and Engineering A. 280, 124–127.

Wang, Y., Li, H.-T., & Fan, Z. (2012). Oxidation of Aluminium Alloy Melts and Inoculation by Oxide Particles. Transactions of the Indian Institute of Metals, 65(6), 653–661. doi:org/10.1007/s12666-012-0194-x

Wood, G. C. (1970). High-temperature oxidation of alloys. Oxidation of Metals, 2(1), 11–57. doi:org/10.1007/BF00603581

Wu, R., Qu, Z., Shu, D., Wang, J., & Sun, B. (2007). The Effects of Purge Gases on the Hydrogen Content and Mechanical Properties of Spray-Degassed Al. Journal of Materials, (May), 62–64.

Xu, H., Han, Q., & Meek, T. T. (2008). Effects of ultrasonic vibration on degassing of aluminum alloys. Materials Science and Engineering: A, 473(1–2), 96–104. doi:org/10.1016/j.msea.2007.04.040

Xu, H., Jian, X., Meek, T. T., & Han, Q. (2004). Degassing of molten aluminum A356 alloy using ultrasonic vibration. Materials Letters, 58(29), 3669–3673. doi:org/10.1016/j.matlet.2004.02.055

Xu, H., Meek, T. T., & Han, Q. (2007). Effects of ultrasonic field and vacuum on degassing of molten aluminum alloy. Materials Letters, 61(4–5), 1246–1250. doi:org/10.1016/j.matlet.2006.07.012

Xu, Z. B., Zou, Y. Z., Gu, H., & Zeng, J. M. (2007). Investigations on Hydrogen Content Change in Melt Aluminum during Casting under Adjusted Pressure. Key Engineering Materials, 353–358, 3059–3062. doi:org/10.4028/www.scientific.net/KEM.353-358.3059

Yadav, N., & Karunakar, D. B. (2011). Effect of Process Parameters on Mechanical Properties of the Investment Castings Produced by using Expandable Polystyrene Pattern. International Journal of Advances in Engineering & Technology, 1(3), 128–137.

Yadav, N., Singh, A. K., Bhat, M. N., Sahu, S., & Kumar, S. (2013). Effect of Process Parameters on the Surface Roughness of A713 Alloy Castings produced by Investment casting process. International Journal of Emerging Technology and Advanced Engineering, 3(3), 543–548.

Ye, J., & Sahai, Y. (1996). Interfacial Behavior and Coalescence of Aluminum Drops in Molten Salts. Materials Transactions, Japan Institute of Metals, 175–180.

Yoon, E., Kim, J., Choi, J., & Kwon, H. (2002). Effects of electromagnetic force on the removal of alumina particles in molten A356 aluminum alloy. Journal of Materials Science Letters, 21, 739–742.

Youngblood, D., & Moore, T. (2013, May). Solid Flux Use in the Aluminum Industry. Die Casting Engineer, 16–18.

Yuan, C., Compton, D., Cheng, X., Green, N., & Withey, P. (2012). The influence of polymer content and sintering temperature on yttria face-coat moulds for TiAl casting. Journal of the European Ceramic Society, 32(16), 4041–4049. doi:org/10.1016/j.jeurceramsoc.2012.06.010

Zake-Tiluga, I., Svinka, V., Svinka, R., Zierath, B., Greil, P., & Fey, T. (2016). Thermal conductivity and microstructure characterisation of lightweight alumina and alumina–mullite ceramics. Journal of the European Ceramic Society, 36(6), 1469–1477. doi:org/10.1016/j.jeurceramsoc.2015.12.026

Zayan, M. H. (1990). Model for Nonprotective Oxidation of AI-Mg Alloys. Oxidation of Metals, 34, 465–472.

Zeerleder, A. Von. (1949). Technology of Light Metals (2nd ed.). Elsevier Publishing Company, Inc.

Zhao, J., Chai, H., & Zhang, F. (2009). Formation of Al_2O_3/Al Composites by Directed Melt Oxidation of Al-Si-Zn Alloy. Journal of Materials Engineering and Performance, 19(1), 46–51. doi:org/10.1007/s11665-009-9412-z

Zhao, L., Pan, Y., Liao, H., & Wang, Q. (2012). Degassing of aluminum alloys during re-melting. Materials Letters, 66(1), 328–331. doi:org/10.1016/j.matlet.2011.09.012

Zhou, M., Li, K., Sun, B. D., Shu, D., Ni, H. J., & Wang, J. (2002). A fluxing method to remove inclusions from molten aluminum. Journal of Materials Science Letters, 21, 1285–1287.